2018

Swine Finishing Room Air Infiltration: Part 2. Infiltration as Affected by Room Characteristics

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Abstract

Data collected on 17 swine finishing rooms from the Midwest region of the United States was used to study the relationship between infiltration rate and selected room characteristics. Effect of individual room characteristics on room infiltration rate were tested by simple linear regression (SLR) while multiple linear regression (MLR) was used to develop models for improved prediction. SLR results revealed that the total (It) and other (Io; non-curtain/fan locations) swine finishing room infiltration rates were inversely related to room width and directly related to room length and ceiling height. As expected, rooms with higher curtain end pocket overlap, curtain closure overlap distance, and in excellent condition had reduced curtain infiltration (Ic). To reduce fan infiltration (If), fan and pump-out cover perimeter and fan area should be minimized. Power law equations fitted for groups of rooms were found ineffective in accounting for the large variability in infiltration rates of swine finishing rooms as compared to MLR models. MLR models developed for It and Io prediction at 10, 20, and 30 Pa pressure differences were found to improve the prediction over power law models for groups of rooms. At 20 Pa, prediction differences compared with individual room measurements for It rate using the suggested MLR model, as compared to power law models for groups of rooms, were less by at least 61%; whereas, in the case of Io rate, prediction differences compared with individual room measurements were less by at least 49%. Recommendations made in this article, with respect to the relationship between a particular room characteristic and room infiltration rate, could be used as guiding principles along with other design criterion to reduce infiltration rates in remodeled and new swine finishing rooms.

Keywords

Infiltration, Swine finishing rooms, Ventilation

Disciplines

Agriculture | Animal Sciences | Bioresource and Agricultural Engineering

Comments

This article is published as Jadhav, Harishchandra T., Steven J. Hoff, Jay D. Harmon, and Daniel S. Andersen. "Swine Finishing Room Air Infiltration: Part 2. Infiltration as Affected by Room Characteristics." *Applied Engineering in Agriculture* 34, no. 4 (2018): 735-745. DOI: 10.13031/aea.12559. Posted with permission.

SWINE FINISHING ROOM AIR INFILTRATION: PART 2. INFILTRATION AS AFFECTED BY ROOM CHARACTERISTICS

H. T. Jadhav, S. J. Hoff, J. D. Harmon, D. S. Andersen

ABSTRACT. *Data collected on 17 swine finishing rooms from the Midwest region of the United States was used to study the relationship between infiltration rate and selected room characteristics. Effect of individual room characteristics on room infiltration rate were tested by simple linear regression (SLR) while multiple linear regression (MLR) was used to develop models for improved prediction. SLR results revealed that the total (I_t) and other (I_o; non-curtain/fan locations) swine finishing room infiltration rates were inversely related to room width and directly related to room length and ceiling height. As expected, rooms with higher curtain end pocket overlap, curtain closure overlap distance, and in excellent condition had reduced curtain infiltration (I_c). To reduce fan infiltration (I_f), fan and pump-out cover perimeter and fan area should be minimized. Power law equations fitted for groups of rooms were found ineffective in accounting for the large variability in infiltration rates of swine finishing rooms as compared to MLR models. MLR models developed for I_t and I_o prediction at 10, 20, and 30 Pa pressure differences were found to improve the prediction over power law models for groups of rooms. At 20 Pa, prediction differences compared with individual room measurements for I_t rate using the suggested MLR model, as compared to power law models for groups of rooms, were less by at least 61%; whereas, in the case of I_o rate, prediction differences compared with individual room measurements were less by at least 49%. Recommendations made in this article, with respect to the relationship between a particular room characteristic and room infiltration rate, could be used as guiding principles along with other design criterion to reduce infiltration rates in remodeled and new swine finishing rooms.*

Keywords. *Infiltration, Swine finishing rooms, Ventilation.*

Negative pressure mechanical ventilation systems are prominently used in livestock and poultry facilities to control the inside environment. Good indoor air quality is a necessity for animal health and high productivity. Continuous release of sensible and latent heat, CO_2 from animals, and NH_3 and H_2S released from manure are some of the major sources of inside air contamination. Ventilation forces outside air through the barn, which dilutes and removes indoor air contaminants (ASHRAE, 2013). In the mechanical ventilation process, air enters into the barn through planned and unplanned inlets simultaneously. Unplanned air entry into a room (i.e., infiltration) is an integral part of any negative pressure ventilation process. Many disadvantages of infiltration are reported in the scientific literature related to animal environment control including infiltration effects on air distribution in a room, deterioration of building components, and animal comfort (see Jadhav et al., 2018).

Infiltration data from 17 swine finishing rooms was collected and power law models were developed for prediction of infiltration rates of individual and groups of rooms. In addition, selected barn characteristics were used to generate ventilation design-ready multiple linear regression (MLR) infiltration models. Developed MLR models were compared with power law models for groups of rooms, with the objective to define their prediction accuracy. Also, an attempt was made to define the effect of individual room characteristics on total infiltration (I_t) and individual component infiltration rates for curtains (I_c), fans and pump-outs (I_f), and the overall room envelope (I_o). These results were used to develop a set of guiding principles that might be useful to reduce infiltration rates of existing and new swine finishing rooms.

Submitted for review in August 2017 as manuscript number PAFS 12559; approved for publication by the Plant, Animal, & Facility Systems Community of ASABE in June 2018.

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MATERIALS AND METHODS

TEST PROCEDURE

Nineteen swine finishing rooms using the negative pressurization method were tested for their infiltration potential. Air infiltration into mechanically ventilated swine finishing rooms was quantified using procedures outlined in Canadian General Standards Board standard CGSB 149.15-96 (1996) and the American Society for Testing Materials standard ASTM E779-10 (2010). Both standards are suited for single

Vol. 34(4): 735-745 ISSN 0883-8542 https://doi.org/10.13031/aea.12559

zone rooms typical of swine finishing and most other livestock and poultry rearing facilities. The majority (18 out of 19) of the rooms were tested by following the procedure in standard CGSB 149.15-96. This standard (CGSB 149.15-96) is used when the installed air handling capacity of the room is capable of producing static pressure differences up to 60 Pa or its air handling capacity lies in the range of 1 to 2.5 L s^{-1} m^{-2} of building envelope (CGSB, 1999). All rooms tested, with the exception of one room, satisfied this CGSB 149.15-96 criterion. The exception room was tested by following both the CGSB 149.15-96 and ASTM E779-10 standards. For this exception room, the building's air handing system along with one externally fitted variable speed fan (into the room entry door) was used to develop the desired static pressure difference analogous to common blower door procedures (ASHRAE, 2013).

During field testing, static pressure differences were generated across the room envelope by exhausting varied quantities of air from the room. Three pressurization tests – I, II and III were conducted on each room. Test I, called the total infiltration *(I_t)* test, was conducted with the primary inlet system sealed while allowing all other building characteristics to remain as in production during minimum ventilation. For all rooms tested, the primary inlet system consisted of ceiling inlets in 1 to 3 rows along the long-axis of the room, dependent on room width. Test II, designed to isolate curtain (I_c) infiltration, was conducted with the primary inlet and all curtain perimeters sealed. Test III, designed to isolate fan (I_f) infiltration, was conducted with the primary inlet, curtain perimeter, and all fan and pump-out cover locations sealed. The infiltration remaining after Test III was designated as other (I_o) infiltration. In all three tests (I, II, III) a minimum of five static pressure differences (points) were generated by exhausting five different air flow rates from the room (CGSB, 1999). The exhaust air flow rates were adjusted such that the static pressure difference spanned between 0 and 60 Pa. The difference between infiltration rates of Tests I and II was quantified as I_c infiltration and the difference between infiltration rates for Tests II and III was quantified as I_f infiltration. The infiltration measured during Test III indicated infiltration through other building components such as ceiling panels and wall-to-ceiling joints. While performing Tests I, II and III, combinations of duct tape, 6-mil plastic, and reinforced polyethylene sheets were used as sealing material. Jadhav et al. (2018) outlines specific details on testing procedures.

Along with the infiltration test data, data on room characteristics including room age, layout, length, width, height, floor and envelope areas (described later), internal volume, and curtain/fan perimeters (described later) were also recorded. Weather data including temperature, relative humidity, wind speed, and altimeter setting was obtained from a weather station closest to each test site. An official calculator provided by the National Weather Service website (http://www.srh.noaa.gov/epz/?n=wxcalc_stationpressure) was used to obtain atmospheric pressure at each test site from altimeter settings. Google earth (https://www.google.com/earth/) was used to retrieve test site elevations.

Testing Equipment and Accuracy Requirements

The precise measurement of exhaust fan air flow rate and static pressure difference across a test room governs the accuracy in infiltration quantification (CGSB, 1996). In this study, the Fan Assessment Numeration System (FANS) was used to measure *in-situ* fan air flow rates (Gates et al., 2004). The FANS unit consists of an array of propeller anemometers, which traverse vertically. Velocities by sweep area are integrated to achieve an air flow rate. During actual testing, the FANS unit was placed upstream of the fan in operation. Leakage paths between the frame of the FANS unit and room wall were sealed so that all the air exhausted by the fan was forced to pass through the FANS unit. For all tests conducted, each individual infiltration air flow rate was measured twice. Combinations of inclined manometers with ±0.005 in. (±0.13 mm; ±1.244 Pa) water column (in. wc) reading resolution and micro-manometers with ± 0.001 in. wc (±0.03 mm; ±0.249 Pa) reading resolution were used to measure static pressure difference across the room envelope. A minimum of two manometers were used at opposite sidewalls of the tested room

Data Correction and Infiltration Prediction

Tests I, II, and III were performed on all swine finishing rooms and at least five data points, exhibiting the relationship between changing exhaust air flow rate and static pressure difference, were generated for each individual test. CGSB standard 149.15-96 (1996) recommends correction of measured infiltration rates for differences in test and calibration temperatures. To minimize the errors due to variation in temperatures from site to site and to maintain uniformity in correction, all the measured infiltration air flow rates were corrected from calibration temperature to standard mean sea level pressure and temperature conditions defined as 101.325 kPa at 15°C. The infiltration rates reported at this standard sea level condition are designated as 'standard' (total, curtain, fan and other) infiltration rates. Two Fan Assessment Numeration System (FANS) units (FANS Model Numbers 30-0010 and 42-0002) were used for this study, both calibrated at 25.56°C (78°F) at BESS laboratory (http://bess.illinois.edu/). Correction of measured testing location conditions to standard conditions and subsequent correction to testing conditions at any future location are outlined in Jadhav et al. (2018). All infiltration rates are presented as an air exchange per hour (ach) with the internal volume excluding the pit and attic volumes.

Room Characteristics Measured

Room characteristics which directly or indirectly affect I_t and component infiltration rates (i.e., I_c, I_f, and I_o) of rooms were measured for all tested rooms. They included both numerical and categorical characteristics. How a particular characteristic affects infiltration area, infiltration rate, and overall room physics was considered while selecting these characteristics. Room characteristics were also used to develop multiple linear regression models useful for infiltration prediction. For each swine finishing room, 40 original barn characteristics (e.g., length, width, etc.) were measured and nine more characteristics were derived (length to width ratio, etc.) from the measured characteristics.

Categorical room and/or barn characteristics, such as barn builder, barn layout, pit type, ceiling material, and primary planned inlet type were collected. Barns were built by either a professional contractor or individual owner. All rooms tested originated from four distinct barn construction layouts (fig. 1) identified as single (S) barns (one large room per barn), double-wide barns (two side-by-side single rooms with one common roof), H-type barns (two end-to-end single rooms per barn with two barns connected by a walkway), and double-wide + H-type barns (two side-by-side single rooms with one common roof per barn with a connecting hallway to an adjacent similar barn). Additionally, double-wide barns, H-type barns, and double-wide + H-type had two or more rooms in a barn and were collectively termed as multi-room (MR) barns. The rooms provided with external manure storage tanks were designated as shallow pit rooms, whereas those with only internal manure storage arrangement were termed as deep pit rooms. On the basis of ceiling material used, rooms were categorized as metal, plastic, and polyethylene rooms. Furthermore, rooms with plastic and polyethylene ceilings were re-designated as non-metal ceiling rooms. All rooms tested used one of four types of primary planned inlets (fig. 2), consisting of continuous or non-continuous rectangular ceiling inlets (fig. 2a, b), baffled bi-flow inlets (fig. 2c), or louvered 4-way inlets (fig. 2d).

The numerical room characteristics measured were divided into three sub-groups, related to whole room, curtains, and fans. Important characteristics measured on a whole room basis were floor and ceiling area, ceiling height, internal volume, wall area, envelope area, primary planned inlet perimeter, and door perimeter. Internal room length and width were used to determine floor and ceiling areas. The vertical distance between room floor and ceiling was reported as the ceiling height. Internal volume was calculated from the product of internal length, internal width, and ceiling height. Internal volume excludes the pit and attic volumes. In cases where room width was not uniform, actual dimensions of internal width and length were used to calculate the internal volume of the room. Internal wall dimensions were used to calculate the areas of two side walls and two end walls. End and side wall areas were added together to determine total wall area of a room. Wall area plus ceiling area was termed as room envelope area. In all four primary inlet cases (fig. 2), the primary inlet perimeter was defined as the total distance where the inlet was attached to the ceiling. Internal perimeters of all door frames added together defined the total door perimeter of a room.

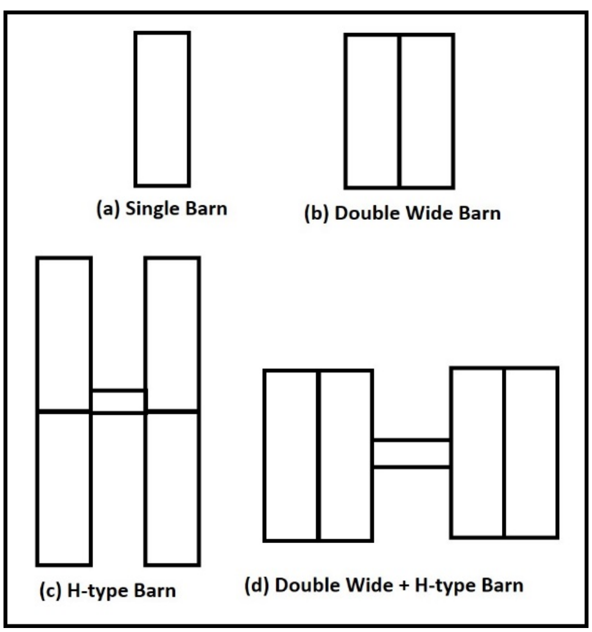

Figure 1. Construction layout of swine finishing barns with the associated rooms within barn.

The important curtain-related characteristics measured included curtain vent perimeter, curtain end pocket overlap distance, curtain closure overlap distance, curtain opening gap, and curtain hole area (fig. 3). Perimeters of all side and end wall openings in a room, over which curtains were fitted, were combined together and designated as total curtain vent perimeter of a room. Overlap of a curtain on the shorter end over an adjacent side or end wall was designated as a curtain end pocket. For each curtain end pocket, curtain overlap was measured at four equidistant locations (out of which two were end points) along the length of the end pocket (i.e., height of the curtain) and an average overlap was calculated for an individual end pocket. Then, the weighted average of overlaps of all end pockets, based on their lengths, was calculated to obtain curtain end pocket overlap distance for a room. Curtain top overlap on side or end wall curtains ─ just above the curtain open gaps, were measured at 3 m intervals and the average overlap was calculated for each curtain in a room. All curtains from all tested rooms opened from top to bottom. Curtain top overlap was measured when the curtains were in the fully closed position as established by the controllers limit switch. The weighted average of all curtain overlaps, based on curtain length, was calculated and designated as curtain closure overlap distance for a room. In some cases there existed a gap between the curtain and a wall when fully closed. This was due to short curtains or because of improper curtain closure. Gaps between curtain top end (length side) and a wall and two side ends (along the side width) of a curtain and wall were measured for each curtain and added together to get curtain opening gap area for a room. Any horizontal gaps between curtain ends and walls, when there existed some curtain overlap, were not included while measuring curtain opening gap. Also, the total area of holes in all curtains was measured. Curtain opening gap area and curtain hole area together formed total open area for a curtain. One unique indicator – describing the physical status of all curtains in a room, based on total curtain open area, was assigned to each room. Rooms with no visible holes or gaps (n=6; table 1) were categorized as ‘excellent’, whereas rooms having up to 400 cm^2 (n=9) total curtain open area (hole + gap areas) were categorized as ‘good’, and more than 400 cm^2 (n=2) total curtain open area were categorized as ‘fair’. The separation at 400 cm^2 was an obvious break-point in the available data set.

Figure 2. Ceiling inlet styles encountered in study.

Fan related barn characteristics measured were fan perimeter, pump out cover perimeter, fan area, and backdraft shutter area. Two different types of fans were found on the swine finishing rooms tested – wall fans and pit fans. Wall fans were fitted either into side or end walls. Pit fans were fitted on pump outs – located outside a room and connected internally to the manure pit. Pit fans were connected to pump-outs using pit-to-fan transition sections. A transition section was connected to the pump out cover at one end and to a rectangular fan base at the other end (fig. 4). Some pump outs were exclusively intended for pump access and not provided with pit fans. Such pump outs were closed with a removable cover during normal operation. For wall fans, the wall attachment perimeter was measured; whereas, in the case of pit fans, the perimeter was measured at the rectangular base of these fans – where they were attached to the pit-to-fan transition section. Fan perimeters (wall and pit) were added together to determine total fan perimeter for a room. Perimeters of all covers provided on all pump outs (with or without pit fans) were added together to determine the total pump out cover perimeter for a room.

Prediction Equations for Infiltration as Affected by Room Characteristics

The interrelationship between infiltration and barn characteristics was explored statistically using simple linear regression (SLR). Infiltration rates recorded for all 17 rooms were grouped together and then analyzed against selected

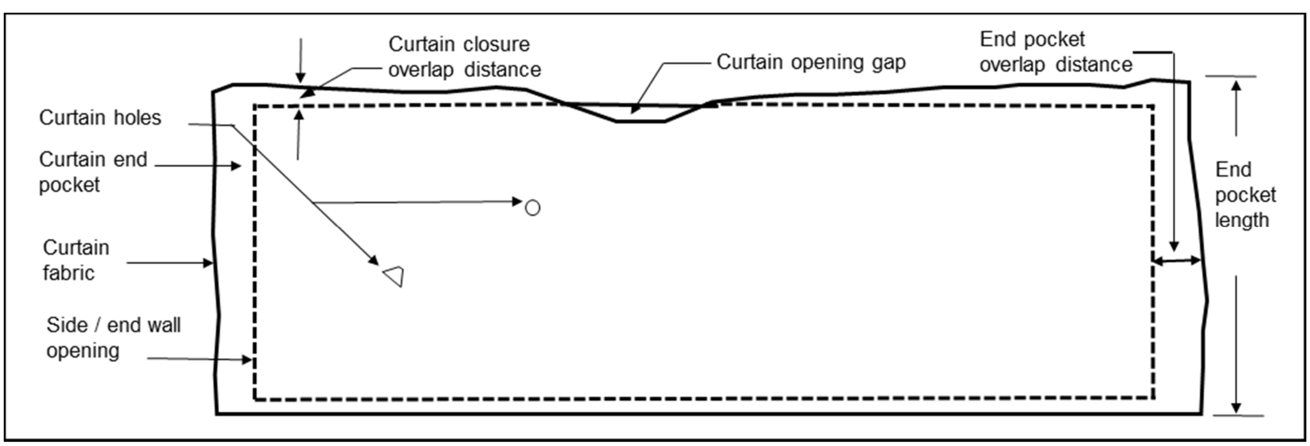

Figure 3. Sidewall and end-wall curtain related characteristics measured.

Figure 4. Typical pit fan setup displaying interconnections between pump out, pump-out cover, and cover-to-fan transition.

room characteristics. This analysis was carried out to test the effect (positive or negative) of each room characteristic on infiltration rate. All the regression tests were performed at the 95% confidence level. Room characteristics showing significant effects on infiltration rate were further examined by taking their physical association into consideration and then assessing the interrelationship between a room characteristic and its effect on infiltration area, thus on room infiltration rate.

The selected room characteristics are presented in table 1 categorized by room number as originally presented in Jadhav et al. (2015). From this original study, rooms 13 and 19 were discarded due to non-compliance with standard CGSB 149.15-96 (1996).

Multiple linear regression (MLR) models were developed from room characteristics as explanatory variables and infiltration rate as a response variable. I_t and I_o rates were used for the analysis. MLR I_t and I_o prediction models were developed at 10, 20, and 30 Pa static pressure differentials, representing common operating pressure differentials for swine housing ventilation design. The MLR modeling was executed by following stepwise model fitting using JMP (SAS, Inc., Cary, N.C.). To select the best MLR model, the corrected Akaike information criterion (AICc), Bayesian information criterion (BIC), R^2, R^2_{adj}, PRESS, and Press RMSE statistics were used. AICc, BIC, PRESS, and Press RMSE were compared for their respective minimum values, while R^2 and R^2_{adj} were compared for their respective maximum. AICc and BIC are commonly used criterion to select an appropriate model (JMP, 2017). In MLR modeling, use of more independent variables, mostly done to increase the model accuracy, may lead to over fitting. AICc and BIC indices prevent over fitting by introducing a penalty term for the number of independent variables used in the model. Also, PRESS (predictive residual sum of squares) and Press RMSE are the major model quality related indicators used in predictive modeling (JMP, 2017). PRESS is an estimation of prediction error using leave-one-out cross validation. Residual plots were observed for their symmetrical pattern and constant spread throughout the range. By following this criterion, at each pressure difference (i.e., 10, 20, and 30 Pa), the top two ranked MLR models were selected for I_t and I_o rate prediction. No more than three predictor variables were included in any MLR model due to the limited sample size. MLR analysis was not performed on I_c and I_f rates.

Table 1. Selected room characteristics of swine finishing rooms tested. Original room numbers 13 and 19 (Jadhav et al., 2015) excluded from analysis due to non-compliance.

Room Number	Width (m)	Length (m)	CH[a] (m)	Barn Layout[b]	Ceiling Material[c]	CVP[d] (m)	CCOD[e] (m)	COGA[f] (cm^2)	CHA[g] (cm^2)	FP[h] (m)	POCP[i] (m)	PIP[j] (m)
1	12.19	60.96	2.44	MR	M	144.7	0.11	0	0	41.05	25.6	118.3
2	12.19	58.52	2.44	S	M	142.3	0.14	0	11.42	33.12	0	30.48
3	12.19	58.52	2.44	S	M	142.3	0.16	0	33.94	33.12	0	30.48
4	12.19	58.52	2.44	S	M	142.3	0.12	0	56.45	33.12	0	30.48
5	12.19	58.52	2.44	S	M	142.3	0.08	0	39.68	36.22	26.82	52.12
6	12.19	58.52	2.44	S	M	143.1	0.05	45.74	18.32	36.22	26.82	52.12
7	12.19	43.59	2.44	S	M	175.9	0.09	0	5.060	17.27	24.38	34.14
8	12.19	43.59	2.44	S	M	175.9	0.10	0	485.7	18.49	24.38	34.14
9	15.24	43.59	2.44	S	NM	175.9	0.11	0	0.7700	20.01	14.63	42.52
10	12.19	37.80	2.29	MR	M	151.7	0.02	367.7	757.4	16.92	4.780	42.52
11	15.24	52.88	2.44	MR	NM	210.3	0.14	0	0	24.59	29.26	52.53
12	15.24	52.88	2.44	MR	NM	210.3	0.11	0	0	24.79	29.26	54.20
14	15.24	52.88	2.44	MR	NM	210.3	0.08	0	0	24.79	29.26	54.20
15	12.19	62.18	2.44	MR	NM	144.1	0.10	0	0	38.91	24.38	115.7
16	12.19	62.18	2.44	MR	NM	144.1	0.09	0	26.38	41.25	24.38	115.7
17	18.36	72.24	2.29	MR	NM	303.7	0.11	0	0	65.38	36.58	82.30
18	18.36	72.24	2.29	MR	NM	298.4	0.09	0	13.92	65.38	36.58	82.30

[a] Ceiling height.
[b] Single (S) or multi-room (MR) barn.
[c] Metal (M) or non-metal (NM) ceiling.
[d] Curtain vent perimeter.
[e] Curtain closure overlap distance.
[f] Curtain opening gap area.
[g] Curtain hole area.
[h] Fan perimeter.
[i] Pump out cover perimeter.
[j] Primary inlet perimeter.

Results and Discussion

Results on the relationship between room characteristic, power law infiltration models, and MLR infiltration models are presented and discussed in this section.

Selected Room Characteristics and Power-Law Models

Using the infiltration test data collected on individual rooms, the power-law models fitted on the combined data for groups of rooms can be used to predict standard infiltration rates. The power law models for these room groups are presented in table 2. Group power law models are compared with individual room (IR) power-law and MLR models elsewhere in this article. The power law models for individual rooms are not presented here, but their results are summarized in figures 6, 7, 9, and 10 (individual room power law models can be found in Jadhav et al., 2015).

Room Characteristics and Infiltration

Results with statistical significance ($p<0.05$) associated with important room characteristics affecting infiltration are presented in this section. Room characteristic effects on I_t and I_o infiltration rates are discussed together since the I_o rate was a major portion (about 49%) of the I_t rate. Room characteristics affecting I_c and I_f rates are discussed separately as these were affected uniquely by different associated room characteristics.

Total (I_t) and Other (I_o) Infiltration

Length of room did not significantly affect I_t and I_o rates ($p=0.48$ and 0.84, respectively). Room width affected I_t and I_o rates positively (both $p<0.01$); while, length to width ratio affected them negatively (both $p<0.01$) implying that longer and narrower rooms had significantly less infiltration. For two rooms of equal length, the wider the room the higher the infiltration, possibly because wider rooms with metal ceilings have more rows of ceiling panels with the associated ceiling panel joints and longer end wall/ceiling joint lengths. Room ceiling height negatively affected I_t and I_o rates (both $p<0.01$) with relatively strong correlations (Pearson's r = -0.31 and -0.35, respectively). The width-to-ceiling height ratio affected both I_t and I_o rates positively (both $p<0.01$) as well as the floor-to-wall area ratio (both $p<0.01$). For two rooms of the same length, if the width of a room is less and its ceiling height is greater, then floor-to-wall area ratio of that room will be less in comparison. Floor or ceiling area (both $p<0.01$) as well as internal room volume (both $p<0.01$) affected both I_t and I_o rates positively. Clearly, an increase in floor/ceiling area and internal volume will result in an increased amount of potential infiltration locations.

Other room characteristics tested for I_t and I_o rates such as the number of doors ($p=0.43$ and $p=0.85$, respectively) and door perimeter ($p=0.81$ and $p=0.48$, respectively) were not significant contributors to the I_t and I_o rates (no room had more than two doors). Primary planned inlet perimeter did not significantly affect I_o rate ($p=0.56$); however, it did significantly affect the I_t rate negatively ($p=0.02$). An increase in primary planned inlet perimeter resulted in a decreased infiltration rate but the correlation between primary planned inlet perimeter and I_t rate was weak (Pearson's r = -0.13). This result suggests that the quality of installation of the primary planned inlet system is more important than the total primary inlet perimeter; a finding similar to curtain infiltration discussed below.

Curtain (I_c) Infiltration

The number of curtains and curtain perimeter were not significant contributors to curtain infiltration ($p=0.58$ and 0.15, respectively). However, curtain end pocket overlap distance ($p<0.01$; Pearson's r = -0.30) and curtain closure overlap distance ($p<0.01$; Pearson's r = -0.30) significantly affected I_c. Laboratory results indicate that curtain closure overlap distances of at least 5.1 cm (2 in.) drastically reduced I_c; furthermore, curtain closure of 7.6 cm (3 in.) provided lit-

Table 2. Power-law models to predict standard I_t and I_o rate (air exchanges per hour, ach) of swine finishing room as a function of building envelope pressure difference (Pa).

Room Group Name	Power Law Model Designation	NR[a]	Model ($I = c\,\Delta p^n$)	Standard Errors c	Standard Errors n	95% Confidence Limits Lower c	Lower n	Upper c	Upper n
Power law models to predict standard I_t rate for various barn groups:									
All rooms together	A	17	$I_t = 2.41 \times \Delta p^{0.303}$	0.159	2.01E-02	2.09	0.264	2.72	0.343
Rooms from S[b]	B	8	$I_t = 2.53 \times \Delta p^{0.279}$	0.189	2.28E-02	2.16	0.234	2.91	0.324
Rooms from MR[c]	C	9	$I_t = 2.28 \times \Delta p^{0.327}$	0.242	3.21E-02	1.80	0.263	2.75	0.39
Rooms from M[d]	D	9	$I_t = 2.13 \times \Delta p^{0.350}$	0.186	2.67E-02	1.77	0.297	2.50	0.403
Rooms from NM[e]	E	8	$I_t = 2.61 \times \Delta p^{0.270}$	0.252	2.92E-02	2.11	0.213	3.10	0.328
Room age ≤ 13 years	F	8	$I_t = 2.61 \times \Delta p^{0.270}$	0.252	2.92E-02	2.11	0.213	3.10	0.328
Room age > 13 years	G	9	$I_t = 2.13 \times \Delta p^{0.350}$	0.186	2.67E-02	1.77	0.297	2.50	0.403
Power law models to predict standard I_o rate for various barn groups:									
All rooms together	A1	17	$I_o = 0.369 \times \Delta p^{0.689}$	5.00E-02	3.65E-02	0.271	0.617	0.468	0.761
Rooms from S	B1	8	$I_o = 0.399 \times \Delta p^{0.632}$	5.96E-02	4.10E-02	0.281	0.551	0.517	0.713
Rooms from MR	C1	9	$I_o = 0.405 \times \Delta p^{0.689}$	7.93E-02	5.22E-02	0.248	0.586	0.561	0.792
Rooms from M	D1	9	$I_o = 0.445 \times \Delta p^{0.636}$	8.02E-02	4.91E-02	0.287	0.539	0.604	0.733
Rooms from NM	E1	8	$I_o = 0.301 \times \Delta p^{0.745}$	6.16E-02	5.45E-02	0.179	0.637	0.423	0.853
Room age ≤ 13 years	F1	8	$I_o = 0.301 \times \Delta p^{0.745}$	6.16E-02	5.45E-02	0.179	0.637	0.423	0.853
Room age > 13 years	G1	9	$I_o = 0.445 \times \Delta p^{0.636}$	8.02E-02	4.91E-02	0.287	0.539	0.604	0.733

[a] Number of rooms used to develop model.
[b] Single room barn layout.
[c] Multi-room barn layout.
[d] Metal ceiling barns.
[e] Non-metal ceiling barns.

tle additional infiltration control (Hoff, 2001). For field conditions, higher values of curtain closure overlap distance (i.e., greater than 7.6 cm) was found beneficial in reducing I_c. Higher curtain closure overlap distance might have positively handled other issues such as construction defects in curtain setup (e.g., like non-uniform closure overlap distance) and operational defects (e.g., sagging of ropes used for vertical movement of curtain) arising over operation time.

Curtain opening gap, curtain hole area, and total open area for curtains (all p<0.01; Pearson's r = 0.44, 0.34, and 0.38, respectively) significantly affected I_c rate. Average age of curtain in years (p=0.13) was not significant but the physical status of the curtain was significant (p<0.01). I_c increased as its physical status changed from excellent to good and good to fair. These results indicate that curtain age was not as important as the physical status described by total open area. In summary, within the dimensional ranges of 'excellent' categorized curtains tested, providing end pocket overlap distance of at least 0.37 m and curtain closure overlap distance greater than 0.16 m minimizes I_c rate.

Fan (I_f) Infiltration

Fan infiltration rate (I_f) included the infiltration through fans and pump-outs. The number of wall fans (p=0.52) was not significant, but the number of pit fans (p<0.01) and the total number of fans (p<0.01) positively affected the I_f rate, suggesting that in the total fan count, the pit fans and associated pump-out covers dominated fan infiltration. Pit fans required many attachments (pump-out covers, transition sections, etc.) with the associated joints resulting in potentially more infiltration area. Wall and pit fan perimeter (p=0.04), pump-out cover perimeter (p<0.01), and the ratio of pump-out cover to fan perimeter (p<0.01) affected I_f rate positively, implying that total pump-out cover perimeter dominated fan infiltration. Furthermore, the effect of pump-out cover perimeter was found more prominent than that of wall and pit fan perimeter (Pearson's r = 0.27 and 0.15, respectively). Fan area positively affected I_f (p=0.01), while backdraft shutter area was not significant (p=0.10). A strong negative relationship was observed with the ratio of backdraft shutter-to-fan area (p<0.01; Pearson's r = -0.61). This effect was hard to define physically, requiring additional in-field testing.

MLR Models to Predict Infiltration

The MLR models developed for predicting I_t and I_o rates are reported and discussed here. By following the model development and selection procedure described previously, the top two MLR models were selected at three common static pressure differences (i.e., 10, 20, and 30 Pa) with respect to I_t and I_o rates. In all, 12 models are reported. The room characteristics that appear in any one or more MLR models listed in tables 3 and 4, are summarized in table 1. Room characteristics not listed in table 1 appearing in the MLR models (e.g. width to ceiling height ratio, total open area for curtains, etc.) can be obtained using table 1 data. The mean value of a particular room characteristic for a particular group of rooms appearing in tables 2 and 3 can also be obtained from table 1 data.

MLR Models for I_t Infiltration Rate

The top two MLR models suggested to predict standard I_t rate at 10, 20, and 30 Pa are presented in table 3. The sample residual plot for MLR model K is shown in figure 5.

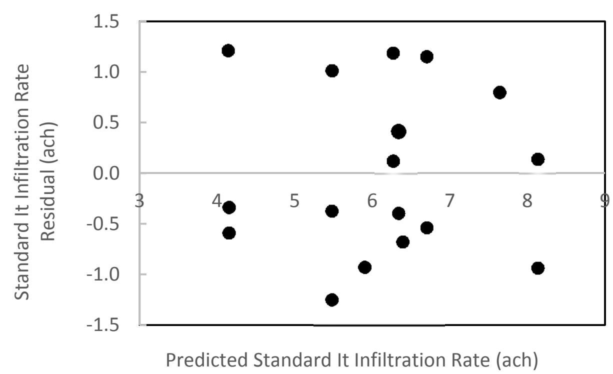

Figure 5. Representative residual plot for MLR model K.

Table 3. MLR models to predict standard I_t rate (ach) of swine finishing rooms.

MLR Model Designation	I_t Infiltration Rate (ach) MLR Models (X = 1 metal ceiling; X=0 for non-metal ceiling)	R^2	$R^2_{adjusted}$	PRESS	PRESS RMSE
	Δp=10 Pa				
H	I_t = -18.97 + 2.251*X[a] + 9.240*LNW[b] - 16.04*CCOD[c]	0.81	0.77	7.49	0.66
I	I_t = -8.349 +2.012*X +7.718*LNWCHR[d] -13.45*CCOD	0.78	0.73	9.64	0.75
	Δp=20 Pa				
J	I_t = - 20.66 + 2.107*X + 5.410*LNCVP[e] -22.68*CCOD	0.85	0.81	8.58	0.71
K	I_t = 43.43 -15.17* CH[f] + 0.05450*POCP[g] - 0.03117*PIP[h]	0.69	0.62	20.3	1.09
	Δp=30 Pa				
L	I_t = -30.48 + 2.234*X + 6.089*LNCVP - 2.125*LNCCOD[i]	0.83	0.79	13.0	0.87
M	I_t = 15.08 + 0.01866*CVP[j] -38.00*CCOD -1.872*LNPIP[k]	0.75	0.70	20.8	1.10

[a] Ceiling material type.
[b] Natural log of (width, m).
[c] Curtain closure overlap distance (m).
[d] Natural log of (width to ceiling height ratio).
[e] Natural log of (curtain vent perimeter, m).
[f] Ceiling height (m).
[g] Pump out cover perimeter (m).
[h] Primary inlet perimeter (m).
[i] Natural log of (curtain closure overlap distance, m).
[j] Curtain vent perimeter (m).
[k] Natural log of (primary inlet perimeter, m).

To study prediction accuracy of the developed MLR models for standard I_t rate, relative to room group models (table 2); both MLR and group models were compared with the power law models for individual rooms (Jadhav et al., 2015). Power law models fitted on an individual room (IR), based exclusively on infiltration data collected for that room, was assumed as the true I_t rate for that room (Walker et al., 1998). Standard I_t rate was predicted for all 17 rooms at 10, 20, and 30 Pa pressure difference using IR power law models (Jadhav et al., 2015), power law models for groups of rooms (models A to G; table 2), and MLR models (models H to M; table 3). Predicted standard I_t rate at 20 Pa are presented in table 4 as a sample set of results. Percent difference of I_t rate predicted at 20 Pa using room group power law models and MLR models over the true IR I_t rate, are also presented in table 4 [(Model-IR)/IR]. The criteria used to assess adequacy of a developed model was established at no more than a ±20% difference compared to each individual room infiltration rate. Among the suggested two MLR models (table 3) at each pressure difference, only the top model (i.e., the first model among the two models reported for each pressure) was used for prediction comparison. Predicted I_t rate at 10 and 30 Pa are not tabulated, but summarized in text.

The average standard I_t rate predicted for all 17 rooms, using IR models at 20 Pa, varied from 3.56 (room 15) to 8.44 ach (room 10), averaging 6.10±1.44 ach (table 4). By comparison, using MLR model J (valid at 20 Pa, table 3), the average standard I_t rate predicted for all 17 rooms varied from 3.96 (room 15) to 8.16 ach (room 10), averaging 6.10±1.32 ach. At 10 Pa, standard I_t rate predicted using IR models varied from 2.36 to 6.92 ach, averaging 4.65±1.16 ach. In contrast, the average standard I_t rate predicted using MLR model H (valid at 10 Pa; table 3) varied from 2.53 to 6.47 ach, averaging 4.65±1.05 ach and at 30 Pa varied from 4.53 to 10.67 ach, averaging 7.17±1.1.73 ach (MLR model L). A graphical comparison between standard I_t rate predicted at 10 Pa for all 17 rooms using the various models is depicted in figure 6.

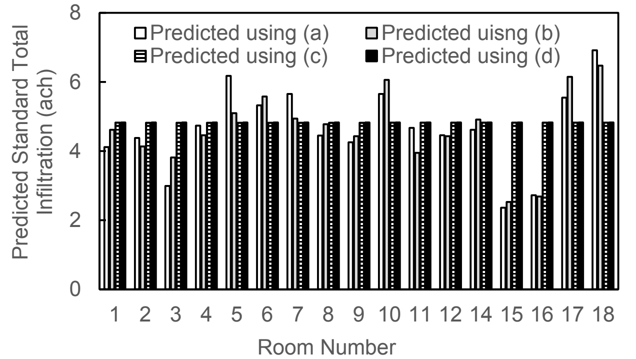

Figure 6. Standard I_t rate (ach) predicted at 10 Pa using selected models: (a) prediction using individual room (IR) power law models, (b) prediction using MLR model H, (c) prediction using models B or C, and (d) prediction using model A (all rooms together).

The difference in standard I_t rate prediction was calculated for room group power law models and MLR models in comparison with IR power law models [(Model-IR)/IR]. The average differences reported are the averages of the absolute value. The maximum average percent prediction difference using room group models (i.e., model A, models B or C, models D or E, or models F or G; whichever applies) was 24±28%, 22±18%, and 22±13% at 10, 20, and 30 Pa, respectively. For MLR models, the average prediction difference was 9±6% (model H vs. IR), 8±5% (model J vs. IR), and 8±5% (model L vs. IR) at 10, 20, and 30 Pa, respectively. A sample comparison of standard I_t rate prediction difference at 30 Pa for MLR model L versus room group models (model A, and models B or C) versus IR predictions is shown in figure 7.

The prediction comparisons summarized previously highlighted the fact that the power law models for groups of rooms (models A to G) were not able to predict standard I_t rate at satisfactory levels (±20%) compared to the developed MLR models. Although a power law model proved to predict accurately the infiltration rate of an individual room (Walker

Table 4. Standard I_t rate (ach) predicted for swine finishing rooms at 20 Pa using different models with percent difference [(Model-IR)/IR] over true I_t.

	Standard I_t Rate (ach) Predicted							Percent Prediction Difference vs. IR Prediction					
Room Number	IR[a] Model	Model A	Models B or C[b]	Models D or E[c]	Models F or G[d]	MLR Model J	MLR Model K	A	B or C	D or E	F or G	J	K
1	5.35	5.96	6.05	6.09	6.09	5.86	4.14	12	13	14	14	10	-23
2	5.11	5.96	5.85	6.09	6.09	5.10	5.48	17	15	19	19	0	7
3	4.23	5.96	5.85	6.09	6.09	4.64	5.48	41	38	44	44	10	30
4	6.49	5.96	5.85	6.09	6.09	5.55	5.48	-8	-10	-6	-6	-15	-16
5	7.46	5.96	5.85	6.09	6.09	6.46	6.27	-20	-22	-18	-18	-13	-16
6	6.39	5.96	5.85	6.09	6.09	7.16	6.27	-7	-8	-5	-5	12	-2
7	7.85	5.96	5.85	6.09	6.09	7.38	6.69	-24	-25	-22	-22	-6	-15
8	6.16	5.96	5.85	6.09	6.09	7.15	6.69	-3	-5	-1	-1	16	9
9	4.97	5.96	5.85	5.85	5.85	4.82	5.90	20	18	18	18	-3	19
10	8.44	5.96	6.05	6.09	6.09	8.16	7.64	-29	-28	-28	-28	-3	-9
11	5.71	5.96	6.05	5.85	5.85	5.10	6.39	4	6	3	3	-11	12
12	5.94	5.96	6.05	5.85	5.85	5.78	6.34	0	2	-1	-1	-3	7
14	6.75	5.96	6.05	5.85	5.85	6.46	6.34	-12	-10	-13	-13	-4	-6
15	3.56	5.96	6.05	5.85	5.85	3.96	4.15	67	70	64	64	11	17
16	3.81	5.96	6.05	5.85	5.85	4.19	4.15	56	59	53	53	10	9
17	7.20	5.96	6.05	5.85	5.85	7.77	8.13	-17	-16	-19	-19	8	13
18	8.27	5.96	6.05	5.85	5.85	8.13	8.13	-28	-27	-29	-29	-2	-2

[a] Individual room "true value".
[b] As barn layout is a categorical variable, model B or C was used, respectively, for rooms from single and multi-room barn layouts.
[c] As ceiling material is a categorical variable, model D or E was used, respectively, for rooms with metal and non-metal ceiling.
[d] Two room age categories were treated as categorical variable, hence model F or G was used respectively for room age ≤ 13 years and > 13 years.

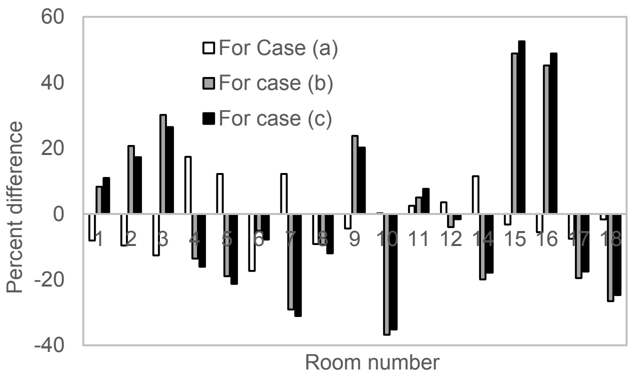

Figure 7. Percent difference [(Model-IR)/IR] in prediction of standard I_t rate at 30 Pa: case (a) depicts percent difference of MLR model L versus IR power law models, case (b) depicts percent difference of model A versus IR power law models, and case (c) depicts percent difference of models B or C versus IR power law models.

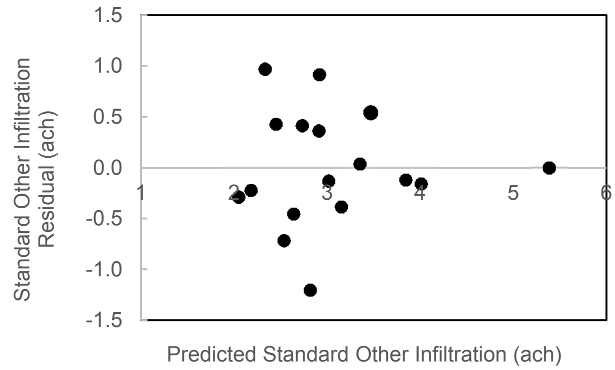

Figure 8. Representative residual plot generated for MLR model Q.

et al., 1998), extension to a group of rooms was found inadequate in tracing room-to-room variability. This might be because livestock and poultry buildings in general and swine finishing rooms in particular, are leakier than residential and other commercial buildings (Masse et al., 1994). Also, a power law model, having pressure difference as the only independent parameter, might not be able to explain large variability in infiltration rates of rooms in a group. To increase end-user value of infiltration data collected on individual rooms, it must be presented for groups of rooms. Average differences (absolute values) in predicting standard I_t rate using the best MLR models (i.e., model H at 10 Pa, model J at 20 Pa, and model L at 30 Pa), as compared to room group power law models (A to G) were less by at least 63% at 10 Pa, 61% at 20 Pa, and 60% at 30 Pa. Also, the percent difference ranges were smaller for all MLR models as compared to any of the power law models developed for groups of rooms.

MLR Models for I_o Infiltration

The top two MLR models suggested to predict standard I_o rate at 10, 20, and 30 Pa are presented in table 5. The sample residual plot for MLR model Q is shown in figure 8.

The prediction accuracy of MLR I_o models, relative to room group I_o models (table 2), was quantified by comparing both models against IR I_o prediction models (Walker et al., 1998). Standard I_o rate predicted at 20 Pa using the different models are presented in table 6. Prediction differences for these models versus IR models, are also tabulated in table 6. Only the top MLR model at each pressure difference was used for comparison. Predicted I_o rate at 10 and 30 Pa are not tabulated, but discussed qualitatively.

The standard I_o rate predicted at 20 Pa for all 17 rooms, using IR models ranged from 1.61 (room 9) to 4.01 ach (room 14) averaging 3.05±0.96 ach (table 6). At 10 Pa, standard I_o rate predicted using IR models varied from 0.89 to 3.46 ach, averaging 1.99±0.70 ach and at 30 Pa varied from 2.28 to 6.96 ach, averaging 3.92±1.17 ach. Standard I_o rate predicted using room group models (model A1, models B1 or C1, models D1 or E1, and models F1 or G1) averaged 1.81±0.13 ach, 2.90±0.17 ach, and 3.83±0.23 ach at 10, 20, and 30 Pa, respectively. In contrast, the standard I_o rate predicted using MLR models varied from 1.24 to 3.46 ach, averaging 1.99±0.56 ach (MLR model N), varied from 2.06 (room 3) to 5.14 (room 10) ach, averaging 3.05±0.82 ach (MLR model P; table 6), and varied from 2.72 to 6.99 ach, averaging 3.92±1.00 ach (MLR model R) at 10, 20, and 30 Pa, respectively. A graphical comparison between predicted standard I_o rate and selected models at 10 Pa is shown in figure 9.

Table 5. MLR models to predict standard I_o rate (ach) of swine finishing rooms.

Model Designation	I_o Infiltration Rate (ach) MLR Models (X = 1 metal ceiling; X=0 for non-metal ceiling)	R^2	$R^2_{adjusted}$	PRESS	PRESS RMSE
	Δp=10 Pa				
N	I_o = 1.503 + 0.005778*COGA[a] + 0.04101*POCP[b]- 0.008552*PIP[c]	0.63	0.55	4.75	0.53
O	I_o = -1.3889 + 0.006918*CVP[d] - 0.9948 *LNCCOD[e] - 0.003917*PIP	0.61	0.53	4.55	0.52
	Δp=20 Pa				
P	I_o = -14.22 + 2.6316*LNCVP[f] -1.402*LNCCOD + 0.6658*X	0.73	0.67	6.75	0.63
Q	I_o = - 9.073 + 1.879*LNCVP - 0.9861*LNCCOD + 0.003172*COGA	0.67	0.60	7.02	0.64
	Δp=30 Pa				
R	I_o = -10.50 + 2.227*LNCVP + 0.001585*OAC[g] -1.157*LNCCOD	0.72	0.66	8.47	0.71
S	I_o = 6.688 + 1.779*X - 20.53*CCOD[h] - 0.02751*PIP	0.73	0.67	10.1	0.77

[a] Curtain opening gap area (cm^2).
[b] Pump out cover perimeter (m).
[c] Primary inlet perimeter (m).
[d] Curtain vent perimeter (m).
[e] Natural log of (curtain closure overlap distance, m).
[f] Natural log of (curtain vent perimeter, m).
[g] Open area for curtains (cm^2).
[h] Curtain closure overlap distance (m).

Table 6. Standard I_o rate (ach) predicted for swine finishing rooms at 20 Pa using different models with percent difference [(Model-IR)/IR] over IR I_o.

Room Number	Standard I_O Rate (ach) Predicted							Percent Prediction Difference vs. IR Prediction					
	IR[a] Model	Model A1	Models B1 or C1[b]	Models D1 or E1[c]	Models F1 or G1[d]	MLR Model P	MLR Model Q	A1	B1 or C1	D1 or E1	F1 or G1	P	Q
1	2.88	2.90	3.19	2.99	2.99	2.63	2.45	1	11	4	4	-9	-15
2	1.96	2.90	2.65	2.99	2.99	2.25	2.18	48	35	52	52	15	11
3	1.76	2.90	2.65	2.99	2.99	2.06	2.05	65	51	70	70	17	16
4	3.30	2.90	2.65	2.99	2.99	2.46	2.33	-12	-20	-9	-9	-25	-29
5	3.15	2.90	2.65	2.99	2.99	3.03	2.73	-8	-16	-5	-5	-4	-13
6	3.39	2.90	2.65	2.99	2.99	3.70	3.35	-14	-22	-12	-12	9	-1
7	2.89	2.90	2.65	2.99	2.99	3.42	3.01	1	-8	4	4	19	4
8	3.27	2.90	2.65	2.99	2.99	3.28	2.91	-11	-19	-9	-9	0	-11
9	1.61	2.90	2.65	2.80	2.80	2.48	2.82	80	64	74	74	54	75
10	5.38	2.90	3.19	2.99	2.99	5.14	5.39	-46	-41	-44	-44	-4	0
11	3.83	2.90	3.19	2.80	2.80	2.61	2.91	-24	-17	-27	-27	-32	-24
12	2.77	2.90	3.19	2.80	2.80	2.95	3.15	5	15	1	1	6	14
14	4.01	2.90	3.19	2.80	2.80	3.39	3.47	-28	-20	-30	-30	-15	-14
15	1.82	2.90	3.19	2.80	2.80	2.09	2.54	59	75	54	54	14	39
16	2.19	2.90	3.19	2.80	2.80	2.23	2.64	33	46	28	28	2	21
17	3.72	2.90	3.19	2.80	2.80	3.91	3.84	-22	-14	-25	-25	5	3
18	3.85	2.90	3.19	2.80	2.80	4.15	4.01	-25	-17	-27	-27	8	4

[a] Individual room (IR) "true value".
[b] As barn layout is a categorical variable, model B1 or C1 was used respectively for rooms from single and multi-room barn layouts.
[c] As ceiling material is a categorical variable, model D1 or E1 was used respectively for rooms with metal and non-metal ceiling.
[d] Two room age categories were treated as categorical variable, hence model F1 or G1 was used respectively for room age ≤13 years and >13 years.

Errors for MLR models and room group power law models were calculated in comparison with IR power law models. The maximum percent prediction difference for room group models (model A1, models B1 or C1, models D1 or E1, and models F1 or G1) was 35±26%, 28±23%, and 27±23% at 10, 20, and 30 Pa, respectively. For MLR models, the average prediction error was 20±23% (model N vs. IR), 14±13% (model P vs. IR), and 14±14% at 10, 20, and 30 Pa respectively. A sample comparison of standard I_o rate prediction errors at 30 Pa for MLR model R and room group models (model A1 and models B1 or C1) versus IR models is shown in figure 10.

The comparison data highlighted that power law models for groups of rooms (models A1 to G1; table 2) were not able to predict standard I_o rate at acceptable levels. Average differences (absolute values) in predicting standard I_o rate using the best MLR models (i.e., model N at 10 Pa, model P at 20 Pa, and model R at 30 Pa), as compared to room group power law models (A1 to G1) were less by at least 37% at 10 Pa, 49% at 20 Pa, and 43% at 30 Pa.

SUMMARY

The data collected on infiltration rate and individual room characteristics of 17 swine finishing rooms were used to define the effect of selected room characteristics on infiltration and to develop MLR models for predicting infiltration rate. The relationship between room characteristics and infiltration rate revealed that the I_t and I_o rates were minimized for narrower and longer rooms with higher ceilings. Rooms with higher curtain end pocket curtain closure overlap and those classified as "excellent" will minimize I_c. Pump-out cover perimeter was a significant source of the overall fan infiltration component, requiring special mitigation attention. Also, in the case of MLR analysis, the MLR model suggested for standard I_t rate prediction at 20 Pa, resulted in an average prediction difference (compared to an individual room) of ±8%; whereas, all room group models performed similarly with average prediction differences (compared to an individual room) of about ±21%. The MLR model suggested for

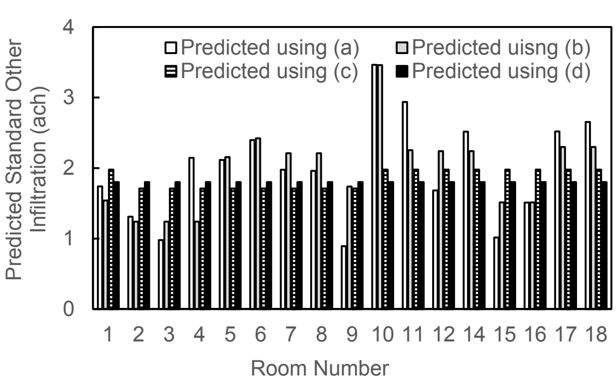

Figure 9. Standard I_o rate (ach) predicted at 10 Pa using various models: (a) prediction using IR power law models, (b) prediction using MLR model N, (c) prediction using models B1 or C1, and (d) prediction using model A1 (all rooms together).

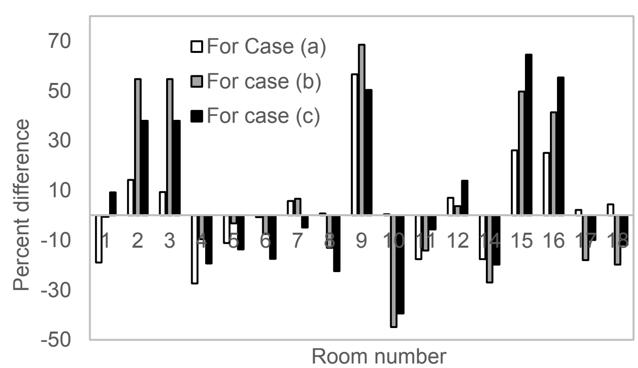

Figure 10. Percent difference [(Model-IR)/IR] in prediction of standard I_o rate at 30 Pa: case (a) depicts percent difference of MLR model R over IR power law models, case (b) depicts percent difference of model A1 over IR power law models, and case (c) depicts percent difference of models B1 or C1 vs. IR power law models.

standard I_o rate prediction at 20 Pa, showed an average prediction difference of ±14%; whereas, all room group models performed similarly with average prediction differences of about ±28%. To conclude, MLR models developed to predict I_t and I_o rates of swine finishing rooms were found superior in predicting infiltration compared to power law models for groups of rooms and deemed suitable for use in swine finishing room ventilation design.

Conclusions and Recommendations

The results presented from a two article series, consisting of Part 1 (Jadhav et al., 2018) and this article (Part 2) on swine finishing room infiltration support the following overall conclusions:

1. Half of the measured infiltration found in a variety of swine finishing facilities originates from non-curtain and fan/pump-out related locations; presumably within the ceiling panel system and the perimeter joints between the ceiling and walls.
2. Curtain age and the number of curtains or total curtain perimeter was not proven to be significant contributors to curtain infiltration. Rather, end-pocket overlap distance (37 cm maximum in study), curtain top overlap distance (16 cm maximum in study), and graded condition of the curtain based on hole area (minimum of zero cm^2 in study) significantly reduced curtain infiltration.
3. Overall, infiltration was lowest for a single-room barn $\leq$13 years old with a non-metal ceiling (plastic or polyethylene). Interestingly, the curtain perimeter was also highest for these room combinations, providing further support for the importance of curtain condition and overlap distances rather than total curtain perimeter.
4. The number of wall fans did not significantly contribute to fan infiltration. Rather, the number of pit fans and the pump-out cover perimeter-to-total fan perimeter ratio significantly increased fan infiltration. Clearly, the amount of pump-out cover perimeter dominates fan infiltration.
5. Compared to the power law models presented by Jadhav et al. (2018), this analysis showed that predicted infiltration rates from developed MLR models better reflected the actual room infiltration rates measured.

The results from this research indicate that, given the current state of swine finishing room construction, the ability of a designed ventilation system to function properly during minimum ventilation periods is severely compromised due to excessive infiltration. Sealing unused curtains, fans, and pump-outs during minimum ventilation periods will eliminate about 50% of the infiltration issue, leaving a troublesome 50% unaccounted for in ceiling panels, wall/ceiling joints, etc. Although costly, foam sealing the attic at all perimeter joints between the ceiling and walls will significantly reduce these “other” sources of infiltration and in turn will dramatically improve minimum ventilation performance. A mock swine finishing room, developed at the Air Dispersion Laboratory (Hoff et al., 2000), was tested for infiltration before and after full attic foaming and indicated an 80% reduction in “other” infiltration. Sealing only joints between the ceiling and walls, versus the entire attic ceiling, would probably not realize this same 80% reduction, albeit a step in the right direction. Precision swine production, a requirement for future protein demands, requires precision in all phases of swine production, starting with the integrity of the shell used to house and produce this protein supply.

Acknowledgements

The authors wish to thank the Iowa Pork Producers Association for funding this research under NPB project 13-213, *Ventilation improvements for controlling swine production systems*. Authors are also grateful to the Indian Council of Agricultural Research, New Delhi for fellowship funding for Dr. H. T. Jadhav. Finally, this work would not have been possible without the support from students Katlyn DeVoe M.S., E.I.T., Craig Blass, E.I.T., and Jessica Miller.

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